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Comparison of Three Underwater Antennas for Use in Radiotelemetry

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Abstract.—The radiation patterns of three versions of underwater radiotelemetry antennas were measured to compare the relative reception ranges in the horizontal and vertical planes, which are important considerations when designing detection systems. The received signal strengths of an antenna made by stripping shielding from a section of coaxial cable (stripped coax) and by two versions of a dipole antenna were measured at several orientations relative to a dipole transmit antenna under controlled field conditions. The received signal strengths were greater when the transmit and receive antennas were parallel to each other than when they were perpendicular, indicating that a parallel orientation provides optimal detection range. The horizontal plane radiation pattern of the flexible, stripped coax antenna was similar to that of a rigid dipole antenna, but movement of underwater stripped coax antennas in field applications could affect the orientation of transmit and receive antennas in some applications, resulting in decreased range and variation in received signal strengths. Compared with a standard dipole, a dipole antenna armored by housing within a polyvinyl chloride fitting had a smaller radiation pattern in the horizontal plane but a larger radiation pattern in the vertical plane. Each of these types of underwater antenna can be useful, but detection ranges can be maximized by choosing an appropriate antenna after consideration of the location, relation between transmit and receive antenna orientations, radiation patterns, and overall antenna resiliency.

Recent advances in technology have resulted in great improvements in the tools available to fishery researchers. Radiotelemetry has benefited from advances in battery technology and miniaturization of circuits, thereby improving transmitters and receivers (Winter 1996; Beeman et al. 1998). Despite these improvements, however, antenna technology has changed little. Fishery researchers can take advantage of the plethora of commercially available aerial antennas because of their broad applications outside the field of animal telemetry, but underwater radio antennas have few uses outside this field. Thus most fishery researchers using telemetry in the aquatic environment either do without underwater antennas or manufacture their own.

Underwater antennas can be useful tools for fishery researchers because they can be used to determine transmitter locations more accurately and detect tagged fish at greater depths than can aerial antennas. Though seemingly contradictory, the increased accuracy of location detection is due to the rapid attenuation of radio waves through water, which results in loss of transmitter signal strength and a reduced range of underwater antennas compared with that of aerial antennas (Winter 1996). Attenuation of radio waves through water and at the air–water interface also limits the depth at which tags can be detected with aerial antennas, whereas an underwater antenna can be placed at almost any depth. These properties of underwater antennas have been used successfully to determine a more precise location of a transmitter that was initially located by using an aerial antenna (Niemela et al. 1993; Martinelli and Shively 1997) and to detect fish passing through areas too deep or inaccessible to be detected with aerial antennas, such as turbine intakes and other underwater passages at hydroelectric dams (Johnson et al. 2000; Skalski et al. 2001).

Underwater antennas made by stripping some

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of the shielding from coaxial cable are commonly used (Knight et al. 1977; Martinelli and Shively 1997; Beeman and Maule 2001), but their flexibility can result in inefficient radiation patterns (i.e., reception) and even breakage in some applications. A rigid antenna mounted with the elements parallel to the transmit antenna would alleviate orientation and breakage problems, improving reception distances and reliability. The simplest antenna design that meets these criteria is the 0.5-wavelength dipole. Unfortunately, no underwater dipole antennas are commercially available, nor have designs for any been published.

To aid in the development and use of underwater antennas in aquatic telemetry, we describe the construction and radiation patterns of stripped coaxial cable (coax), standard dipole, and armored dipole antennas designed to monitor tagged animals below the surface of freshwater. These antenna designs are not new to the field of radio frequency technology but have been adapted, chiefly in size and strength, for use in underwater environments.

Methods

This study was conducted in Drano Lake, a backwater at the confluence of the Little White Salmon River and the Columbia River (river kilometer 261) located near Hood River, Oregon. This site was chosen because of its low water velocities and adequate depth. Low water velocities were required so that divers could alter antenna orientations, and a water depth of approximately 10 m was desired to reduce the effects of radio waves reflected from the lake bottom or water surface during tests.

Antennas.—All receive antennas and the single transmit antenna were constructed on 33.3 m lengths of Belden model 9311 coaxial cable (Belden Electronics Division, Richmond, Indiana). The general characteristics of this Radio Guide (RG) Type 58 A/U cable include an aerial and universal rating (A/U), an outside diameter of 4.9 mm, an impedance of 52 Ω, and an attenuation of 4.8 dB per 33.3 m at a frequency of 150 MHz. All coaxial cables were terminated at the end opposite the antenna with crimp-on bayonet Neill Concelman (BNC) connectors.

Three samples of each of three antenna designs were tested to ensure that variability in construction would be represented. All designs were based on antenna elements of 0.5 wavelengths underwater at a frequency of 150 MHz; this is much shorter than the wavelength in air because the dielectric properties of water lower the speed of propagation. For example, the wavelength of a 150 MHz radio wave in air is 2 m (Merkin 1989), but its wavelength in freshwater is 21.8 cm (at a temperature of 10°C and a conductivity of 150 μS/cm). This value was derived from a model developed by C.G. based on radio frequency theory (Ulaby et al. 1986). Using the following equation to describe the output from this model, one can calculate the approximate underwater wavelength at any frequency from 10 to 510 MHz:

$$\text{wavelength (in meters)} = 32.649 \times \text{frequency (in MHz)}^{-0.9998} \quad (r^2 = 1.0, N = 54).$$

The results are dependent on water temperature and conductivity but are relatively insensitive to changes in either of these variables. For example, changing the temperature from 10°C to 20°C results in a 0.5-cm increase in the underwater wavelength at 150 MHz, and changing the conductivity from 150 to 3,000 μS/cm decreases the value by 0.4 cm. Thus, this equation provides a reasonable approximation under most freshwater conditions.

The stripped coax antenna was the simplest to manufacture. To construct this antenna, all material around the center conductor (the outer jacket, braided shielding, foil, and dielectric material) was removed from the distal 11.4 cm of the coaxial cable (this distance differs slightly from the calculated 0.5 wavelengths at 150 MHz because of numerical rounding). The remaining braided wire center conductor was tinned with solder to prevent the braid from unraveling.

A standard dipole antenna was constructed from Schedule 40 polyvinyl chloride (PVC) pipe and stainless steel bolts and fasteners (Figure 1A). A 14-cm piece of 2.54 cm (inside diameter [i.d.]) PVC was used for the antenna mast. The length of the mast was chosen to maintain a minimum distance of 0.5 wavelengths between the antenna elements and the surface on which the antenna was mounted, to minimize any effects of nearby reflective surfaces on the radiation pattern of the antenna. This distance is specific to the wavelength for which the antenna is designed. Two #10 (10–24) bolts 6.4 cm long were used for the elements of the antenna. Each bolt was attached to the mast wall with a pair of machine nuts 2.54 cm from the end of the pipe. We took care that the bolts inside the pipe did not touch one another, to avoid forming a short circuit. Once mounted in the mast, the outside ends of the bolts were cut to a total length

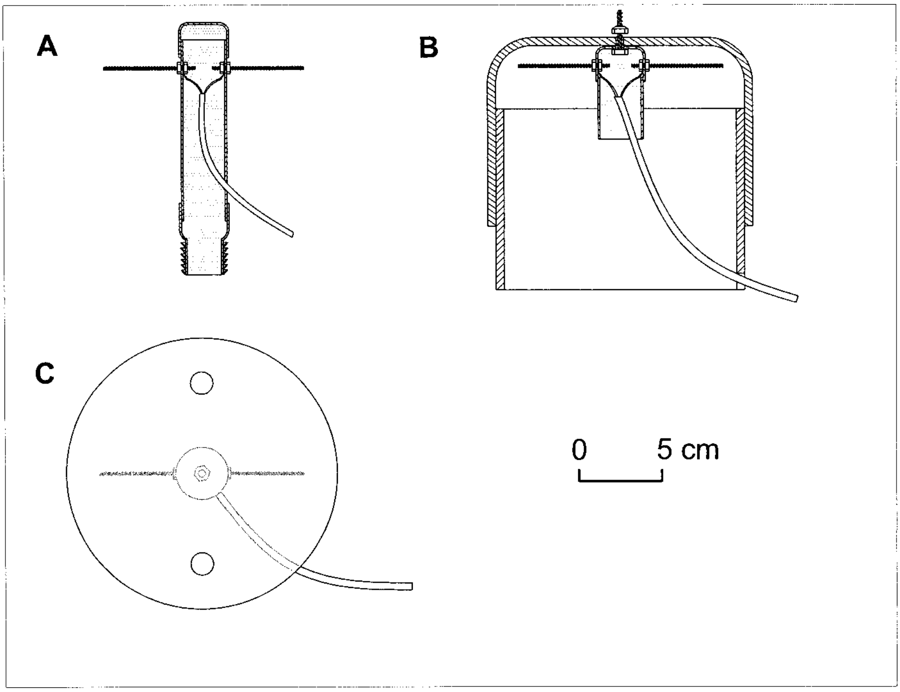

FIGURE 1.—Cross-section of (A) a standard and (B) an armored dipole antenna, and (C) an overhead view of an armored dipole antenna, showing the orientation of the mounting bolt holes to the dipole elements.

of 11.4 cm; we used a jig to ensure that each bolt extended from the mast by an equal length. Attaching the center conductor of the coaxial cable to one bolt and the braided shielding to the other bolt inside the mast completed the connections between the antenna elements and coaxial cable. Using ring terminal connectors on each of the wires simplified making the connections within the confines of the mast (the braided shielding was unraveled from around the core of the coaxial cable and twisted into a single strand of wire). Again, we a were careful to ensure that the center conductor and the shielding did not make contact, to avoid a short circuit. Each antenna was tested with an ohmmeter at this point in the construction and again when the entire process was complete to confirm that no short circuit existed. The shortest possible amount of the center conductor was exposed when stripping the coaxial cable, because the exposed center conductor becomes an antenna once the shielding is removed. For this reason, the materials must be cut consistently for each antenna. Once the connections were completed, a 3.3-cm (i.d.) PVC cap was glued in place with PVC glue. Each antenna was then filled with an epoxy resin to prevent water intrusion, which could corrode the dipole connections and metal parts of the coaxial cable, and to add strength and strain relief. We used a low-odor epoxy that produced little heat when curing (System Three epoxy and System Three hardener # 2; System Three Resins, Auburn, Washington). The mixed epoxy and hardener were poured into inverted antennas held in a plywood rack and allowed to cure.

The third antenna type was an armored version of the standard dipole antenna. This design was developed for use in areas subject to high velocities or high debris loads, in which standard dipole antennas sometimes have broken. The armored dipole antenna is essentially a standard dipole, mounted within a 3.3-cm PVC cap, affixed to the underside of a 12.7-cm (i.d.) Schedule 40 PVC end cap (Figure 1B). The small cap housing the antenna was attached to the center point of the underside of the large cap with a 0.64-cm-diameter bolt, which had been added to the small cap before the antenna components. The bolts forming the dipole elements were mounted in the cap 1.3 cm from the opening of the cap. Once the antenna connections were made, a 5.1-cm length of PVC pipe was glued into the cap to increase the capacity of the epoxy used to maintain watertight connections and provide strain relief. Once assembled and poured with epoxy, the antenna was mounted within the large PVC cap. A 10.2-cm length of PVC pipe was glued into the large PVC cap to maintain at least 0.5 wavelength between the antenna elements and the mounting surface. A small notch cut in the PVC pipe that was glued into the large cap provided an exit for the coaxial cable when the antenna was mounted to a flat surface. The entire antenna assembly was then bolted to a flat steel mounting plate by two 0.95-cm-diameter bolts 15.24 cm long. The mounting bolts were oriented perpendicular to the antenna elements to minimize their effect on the radiation pattern (Figure 1C).

Test apparatus.—An underwater test frame was constructed to produce consistent results and minimize the effects of reflected or interactive surfaces. The system was designed such that any signal bouncing off of a major reflective surface (the lake bottom or air–water interface) would travel at least twice the distance of the direct path to the receive antenna, resulting in minimal influence on the direct wave. Two steel 1.2-m-tall tripods placed 4.6 m apart on the lake bottom at a depth of 9.1 m were used to support 4.6-m-long vertical poles of 5-cm-diameter Schedule 40 PVC for antenna attachment, which resulted in the antenna mounts 4.5 m deep, equidistant between the water surface and the lake bottom. The distance between the vertical poles was maintained by a horizontal PVC support near their tops. Mounts were created for each antenna style to permit rotation in the horizontal and vertical planes.

The radiation pattern around a dipole antenna can be defined by three rotations. A Cartesian reference was used, with the *x*-, *y*-, and *z*-axis labels describing the abscissa, ordinate, and altitude, respectively, when the apparatus was viewed from above. Thus, the line between transmit and receive antennas was designated as the *x*-axis, the line in the horizontal plane 90° from the *x*-axis was designated the *y*-axis, and the vertical line perpendicular to these axes (i.e., toward the water surface) was designated the *z*-axis.

The transmit antenna was affixed in a stationary position so that it would not contribute to changes in signal strength. This antenna was a standard 0.5-wavelength dipole mounted so that the mast was oriented along the *z*-axis and the dipole elements were oriented parallel to the *y*-axis. The transmit antenna was attached to the top of one pole of the test frame and the receive antennas were attached alternately about the top of the other pole of the test frame and rotated to various positions.

The amplitude of transmitted radio waves was measured at the receive antennas to determine the received signal strengths at several orientations of the antennas (described below). A carrier wave with an amplitude of 0 decibels relative to 1 mW (dBm) and a frequency of 150 MHz was produced with an Agilent 8648B signal generator connected to the standard dipole transmit antenna. Amplitudes of the signals received by the test antennas were measured with an Agilent E4401B ESA E-Series spectrum analyzer. The transmitting and receiving equipment was mounted in a 7-m-long aluminum boat anchored approximately 10 m from the underwater test apparatus.

Test conditions.—The receive antennas were mounted on the test frame and rotated through as many as three different patterns. In each test, one measurement of received signal strength was recorded from each of the three antennas of each type at each orientation angle, such that $N = 3$ from each antenna type at each orientation angle. To test the radiation pattern in the horizontal (i.e., *x*–*y*) plane, the receive antenna was mounted with the mast along the *z*-axis and the elements along the *y*-axis, parallel to the elements of the transmit antenna. The receive antenna was then rotated in the *x*–*y* plane with the received signal strength measured at angles of 0°, 45°, 90°, 135°, and 180° relative to the elements of the transmit antenna; the antenna elements of the transmit and receive antennas were parallel at the 0° angle and perpendicular at the 90° angle. The stripped coax antennas were mounted in the *x*–*y* plane and rotated through the same series of angles relative to the elements of the transmit antenna. The horizontal plane test was repeated with one of the standard dipole antennas to determine whether the results between trials were consistent, which would indicate whether the results from the method were repeatable. To test radiation patterns in the vertical plane, the receive antenna mast was mounted parallel to the *x*-axis (with its top nearest the transmit antenna) and the elements parallel to the *y*-axis; the receive antenna was then rotated about the *z*-axis with measurements of received signal strength recorded at angles of 0°, 45°, 90°, 270°, and 315° relative to the elements of the transmit antenna. This test was not performed with the stripped coax antenna type, which has no defined top or sides. Lastly, a test was conducted with the dipole antennas to illustrate the effects of antenna polarization—that is, when transmit and receive antennas were parallel, intermediate, or perpendicular to each other. In this test, each antenna was mounted as in the vertical plane test, but the antenna was rotated around the *x*-axis and signal strengths were recorded at 0°, 45°, and 90°. The results of all tests were measured and expressed in dBm.

Two divers wearing self-contained underwater-breathing apparatus manipulated the antennas through the various orientations. They ensured that the coaxial cables led away from the antennas along the test frame and that nothing (including themselves) was in the vicinity of the antennas to cause potential distortion. Conductivities and water temperatures recorded with a YSI 650 Multiparameter Display System and 600R sonde at several times during the tests were used to describe environmental conditions during testing.

Two-way analysis of variance (ANOVA), followed by Ryan–Einot–Gabriel–Welsch multiple comparisons, was used to test for statistical differences between the average received signal strengths of each antenna type at each orientation angle in each test. The ANOVA model consisted of fixed effects of antenna type (stripped coax, standard dipole, armored dipole) and orientation angle between transmit and receive antennas (as many as five angles between 0° and 315°, depending on the test) as well as their interaction term. Results were considered statistically significant when $P \leq 0.05$.

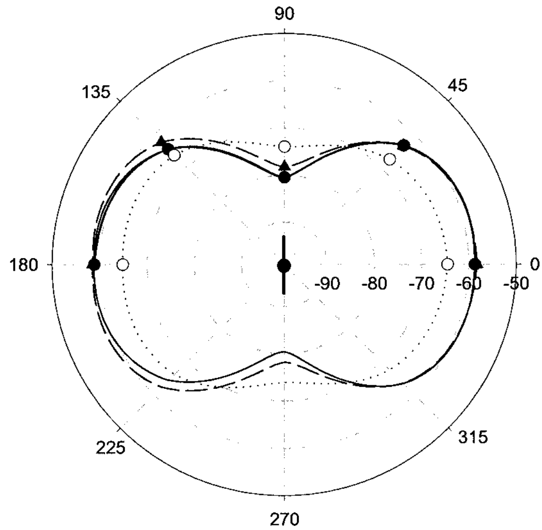

FIGURE 2.—Overhead view of the horizontal radiation patterns of stripped coax (solid line, closed circles), standard dipole (dashed line, closed triangles), and armored dipole (dotted line, open circles) underwater antennas. Smoothed lines are drawn on the basis of the measured values indicated by symbols. Radial data are in units of decibels relative to 1 mW (dBm), angular data are in degrees. Elements of transmit and receive antennas were parallel at 0° and perpendicular at 90°. The dipole diagram at the center (not to scale) indicates the orientation of the receive antenna relative to the radiation patterns.

Results

Signal strength measurements were recorded from the receive antennas in the various orientations between 1045 and 1645 hours on 13 December 2001. The average water conductivity was 37 μS/cm and the average water temperature was 2.8°C at or near the lake bottom (7.9–9.1 m; $N = 4$). The water temperature at a depth of 1.2 m was 5.8°C ($N = 1$).

Horizontal Plane

Shapes of the horizontal radiation patterns of the three antenna types were similar, though received signal strengths differed. Received signals were strongest from the sides of the receive antenna elements and were weakest from their ends, the difference between these orientations being approximately 20 dB within each antenna type (Figure 2). Received signal strengths differed among antenna types ($F = 3.9$; df = 2, 30; $P = 0.0307$) and angle ($F = 33.9$; df = 4, 30; $P < 0.0001$). The ANOVA interaction term was not significant, indicating that the differences among angles were similar among antenna types ($F = 1.8$; df = 8, 30; $P > 0.1$). Received signal strength of the standard dipole was significantly stronger than that of the armored dipole; that of the stripped coax was intermediate (Table 1). In addition, received signal strengths at 90° were significantly weaker than those at the other angles, which did not differ significantly from one another.

Data from the two trials with the same standard dipole antenna during the horizontal plane test indicated that the results from this method were repeatable. Signal strengths differed among the angles ($F = 21.8$; df = 2, 6; $P = 0.0018$) as in the previous tests, but there was no significant difference between the two trials ($F = 0.6$; df = 1, 6; $P > 0.4$), and the differences among angles were similar between trials ($F = 0.3$, df = 2, 6; $P > 0.7$).

Vertical Plane

Shapes of the vertical radiation patterns of the standard and armored dipole antennas were similar, each indicating greater signal strengths overhead than to the ends of the antenna elements (Figure 3). Received signal strengths differed significantly between antenna types ($F = 5.8$; df = 1, 20; $P = 0.0258$) and among angles ($F = 5.2$; df = 4, 6; $P = 0.0049$). The lack of a significant interaction term indicated that differences among

TABLE 1.—Mean received signal strengths during tests of three antenna types. Each value represents the mean received signal strength in decibels relative to 1 mW (dBm) from $N = 3$ antennas of each type; negative values indicate signal strengths less than 1 mW. The stripped coax antenna was only used during the horizontal plane test. Orientation angle is in degrees relative to the transmit antenna elements (0° = parallel). Within each test type, means within rows or columns followed by a common letter were not significantly different (Ryan–Einot–Gabriel–Welsch test; $P > 0.05$).

Orientation angle (°) or mean	Antenna type: Stripped coax	Standard dipole	Armored dipole	Mean
Horizontal plane test				
0	−58.7	−58.6	−64.5	−60.6 z
45	−63.3	−64.0	−67.5	−64.9 z
90	−80.5	−76.1	−74.0	−78.6 y
135	−64.4	−62.3	−66.2	−64.3 z
180	−58.9	−58.6	−64.9	−60.8 z
Mean	−65.2 zy	−63.9 z	−67.4 y	
Vertical plane test				
0		−62.6	−62.4	−62.5 z
45		−69.8	−64.7	−67.3 zy
90		−75.3	−71.5	−73.4 y
270		−73.5	−70.2	−71.8 y
315		−71.3	−63.3	−67.3 zy
Mean		−70.5 z	−66.4 y	
Polarization test				
0		−63.3	−62.7	−63.0 z
45		−67.5	−64.4	−65.9 z
90		−75.3	−76.0	−75.6 y
Mean		−68.7 z	−67.7 z	

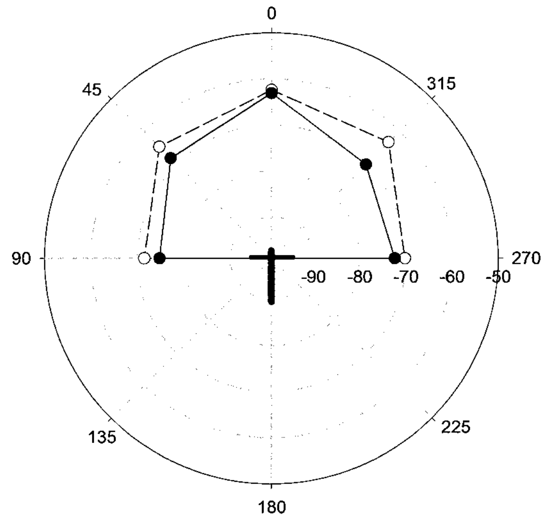

FIGURE 3.—Side view of the vertical radiation patterns of standard dipole (solid line, closed circles) and armored dipole (dashed line, open circles) underwater antennas. Radial data are in units of decibels relative to 1 mW (dBm), angular data are in degrees. Elements of transmit and receive antennas were parallel at 0° and perpendicular at 90°. The dipole diagram at the center (not to scale) indicates the orientation of the receive antenna relative to the radiation patterns.

angles were similar between types ($F = 0.6$; df = 4, 6; $P > 0.6$). The mean signal strength from the armored dipole antenna was significantly stronger than that of the standard dipole, and signals from the 90° and 270° angles were significantly weaker than from the 0° angle, signals from the remaining angles (45° and 315°) being intermediate (Table 1).

Effect of Antenna Polarization

The received signal strength was negatively affected by rotating the standard and armored dipole receive antennas from a parallel polarization (0°) to perpendicular polarization (90°) relative to the transmit antenna. Received signal strength did not differ significantly between antenna types ($F = 0.3$; df = 1, 12; $P > 0.6$), but a significant difference among angles was evident ($F = 15.9$; df = 2, 12; $P = 0.0004$). The interaction term was not significant, indicating that differences among angles were similar between antenna types ($F = 0.3$, df = 2, 12; $P > 0.7$). Average signal strength at the 90° angle was significantly weaker than at the 0° angle and 45° angles, which were not significantly different from one another (Table 1).

Discussion

Our results indicate that received signal strengths differed among antenna types, reception ranges being greatest when the elements of the transmit and receive antennas were parallel. The shapes of the radiation patterns were generally similar between antenna types and were similar to those of 0.5-wavelength dipole antennas in air (Hickman 1997). Exact measurements of radiation patterns may have little practical meaning for most fishery researchers, but knowledge of the shapes and sizes of the radiation patterns are important to consider when using underwater antennas.

The received signal strengths measured during this study were similar to field measurements of Johnson et al. (2000), who were able to detect radio transmitters in juvenile salmonids at ranges between 5 and 10 m from underwater 0.5-wavelength dipole antennas mounted on a Snake River dam. The received signal strengths in our tests of the standard dipole would provide a range of about 7 m to the sides of the antenna element and 4 m from its ends, according to a detection range model (C. G., unpublished) based on a signal from a 150 MHz Lotek Wireless model MCFT-3GM transmitter in water with a conductivity of 150 μS/cm and temperature of 10°C (this transmitter was used in the study by Johnson et al. [2000]; N. Adams, U.S. Geological Survey, personal communication). In contrast, the detection range of the aerial detection system of Johnson et al. (2000) was between 130 and 300 m, illustrating the reduced range and increased position resolution inherent in underwater antennas relative to aerial antennas. Users of telemetry should understand that the best system performance will be realized when both the transmitting and receiving systems are properly designed and that the receive antenna is only one part of the total system.

Each antenna type we describe has useful applications, but there are important differences between them. The stripped coax antenna is the easiest to construct and may be appropriate in applications with low water velocities or where optimal underwater range is not the primary consideration. The dipole antenna types can be used to correct polarization mismatches inherent in some stripped coax applications, provide a receiver antenna that can be kept at a proper distance from reflective surfaces, and will not change orientations during most conditions. The armored version had a slightly shorter range in the horizontal plane and greater range in the vertical plane and is much more resilient than the standard dipole.

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References

Beeman, J. W., P. V. Haner, and A. G. Maule. 1998. Evaluation of a new miniature pressure-sensitive radio transmitter. North American Journal of Fisheries Management 18:458–464.

Beeman, J. W., and A. G. Maule. 2001. Residence times and diel passage distributions of radio-tagged juvenile spring chinook salmon and steelhead in a gatewell and fish collection channel of a Columbia River dam. North American Journal of Fisheries Management 21:455–463.

Hickman, I. 1997. Practical radio frequency handbook, 2nd edition. Biddles, UK.

Johnson, G. E., N. A. Adams, R. L. Johnson, D. W. Rondorf, D. D. Dauble, and T. L. Barila. 2000. Evaluation of the prototype surface bypass for salmonid smolts in spring 1996 and 1997 at Lower Granite Dam on the Snake River, Washington. Transactions of the American Fisheries Society 129: 381–397.

Knight, A. E., G. Marancik, and J. B. Layzer. 1977. Monitoring movements of juvenile anadromous fish by radiotelemetry. Progressive Fish-Culturist 39: 148–150.

Martinelli, T. L., and R. S. Shively. 1997. Seasonal distribution, movements and habitat associations of northern squawfish in two lower Columbia River reservoirs. Regulated Rivers: Research and Management 13:543–556.

Merkin, M. 1989. Physical science with modern applications, 4th edition. Saunders, Philadelphia.

Niemela, S. L., J. B. Layzer, and J. A. Gore. 1993. An improved radiotelemetry method for determining use of microhabitats by fishes. Rivers 4:30–35.

Skalski, J. R., J. Lady, R. Townsend, A. E. Giorgi, J. R. Stevenson, C. M. Peven, and R. D. McDonald. 2001. Estimating in-river survival of migrating salmonid smolts using radio-telemetry. Canadian Journal of Fisheries and Aquatic Sciences 58:1987–1997.

Ulaby, F. T., R. K. Moore, and A. K. Fung. 1986. Microwave remote sensing, active and passive, volume 3. From theory to applications. Artech House, Norwood, Massachusetts.

Winter, J. 1996. Advances in underwater biotelemetry. Pages 550–590 *in* B. W. Murphy and D. W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland.